UCRL-JC-132199
PREPRINT

Brewster's Angle Thin Film Plate Polarizer Design Study from an Electric Field Perspective

C. J. Stolz

This paper was prepared for submittal to the
European Optical Society Symposium on Optical
Systems Design and Production
Berlin, Germany
May 25-28, 1999

April 27, 1999

Lawrence Livermore National Laboratory

Brewster's angle thin film plate polarizer design study from an electric field perspective

C. J. Stolz

University of California, Lawrence Livermore National Laboratory
PO Box 808, L-487, Livermore, CA 94551, USA

ABSTRACT

The electric field magnitude and profile influence the laser-induced damage threshold and morphology of a multilayer coating. Through the use of non-quarter-wave layer pairs in high reflector designs, the electric field peaks are shifted into the low index layers thus reducing the electic fields in the high index layers and interfaces. Similarly the electric field profile in a polarizer can be optimized for low electric fields within the high index layers and film interfaces by proper design selection.

The traditional approach to Brewster's angle thin film polarizer design starts with a long-wave pass design to exploit the angle-induced differential high reflection bandwidths for "P" and "S" polarization. The design is optimized to admittance match the exterior and interior layers of the central stack to the surrounding media (air and glass). This design yields a broad polarizing region with electric field peaks within the high index layers. If a short-wave pass design is optimized, a narrower bandwidth polarizing region is realized with a slightly thicker coating, but the electric field peaks are now shifted to the low index material. In this paper, different starting designs are examined including short-wave pass, long-wave pass, and Fabry-Perot bandpass for electric field profile, polarizing region bandwidth, sensitivity to layer thickness errors, total thickness, and extinction ratio.

Keywords: Thin film polarizer, electric field, and laser-induced damage

1. INTRODUCTION

Thin film Brewster's angle polarizers are typically a fluence-limiting component within a laser system. The laser architecture of the National Ignition Facility (NIF), a 1.8 MJ Inertial Confinement Fusion (ICF) laser currently under construction at the Lawrence Livermore National Laboratory, is significantly impacted by the damage threshold of the intercavity polarizer.[1,2] The polarizer damage threshold is greater in "S" polarization than "P" due to the rapidly decaying standing-wave electric field within the coating. Therefore the laser is designed with the highest fluence beam within the multipass cavity "S" polarized to the thin film polarizer. The polarizer laser damage threshold is still inadequate for complete amplification in the NIF multipass cavity, so a booster amplifier is placed after the polarizer, outside of the main multipass cavity.

One technique for increasing the laser damage threshold of high reflector mirrors is through the use of non-quarter-wave exterior layer pairs to reduce the electric field in the high refractive index material and at the thin film interfaces.[3,4] Work has been published on expanding this theory to include non-normal incidence reflectors and polarizers.[5] Although this technique increases the peak electric field strength within the silica layer, the multilayer damage threshold is increased because of the higher electric field tolerated by the low index material. The importance of low electric fields is experimentally validated by the correlation of electric field peaks at interfaces in high reflector designs with the occurrence of flat bottom pits, an interfacial damage morphology.[6,7]

Significant work has also been done on polarizer designs with respect to the electric field profile. In one damage study, the electric field was significantly increase by improper selection of the overcoat thickness.[8] These coatings damaged at half the fluence of a polarizer with an optimum overcoat thickness. Deep pitting was observed, indicative of the high electric field peaks deep within the coating design. Polarizers have been designed for low electric fields for back reflected beams resulting in increased damage thresholds.[9] Detuned spacer designs were reported to have lower electric fields than edge filter designs.[10] Finally, proper admittance matching has also been shown to reduce peak electric fields in polarizers.[11]

The traditional approach to Brewster's angle thin film plate polarizer design is optimization of a long wave pass (LWP) edge filter by taking advantage of the polarization splitting characteristics observed at non-normal incidence angles.[12-14] The coating is composed of three parts, a central stack for achieving the polarization splitting and two antireflection coatings for

stolz1@llnl.gov

admittance matching the central stack with the incident and exit mediums.[11] Since the coating is at Brewster's angle, the admittance matching is identical for incident and exit mediums to the central stack. Therefore optimization of the designs for this study was restricted to mirror symmetry with respect to the central layer. Edge filters with thick and thin high index layers were also examined due to the use of this approach in reducing the peak electric field in previous work.[5,9]

Another polarizer design that has been used is the Fabry-Perot bandpass filter.[15] The advantage of this design is the use of only quarter-wave and half-wave layers, comparable electric field strength, and greater extinction ratio for similar design thickness. The design has a smaller angular bandwidth than typical LWP designs, but is less sensitive to random thickness errors.

2. DESIGN STUDY

As illustrated in figure 1, polarizing regions of a multilayer interference filter can be exploited on the short-wave and long-wave regions of the reflectance band. In this study six polarizer designs with thirty-six layers of alternating hafnia and silica materials were examined in the short and long wave regions. Each design has a silica overcoat for improved laser damage resistance.[8] The overcoat thickness was determined by selection of the minimum thickness for an electric field minimum at the air film interface, but still exceeding an optical thickness of $\lambda/3$ (λ=1053 nm). These thickness constraints were imposed to minimize the impact of surface contamination and eliminate overlayer delamination, respectively.

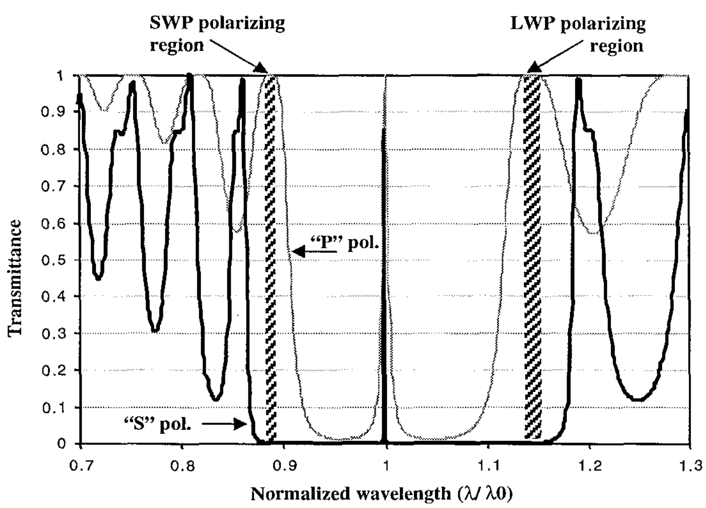


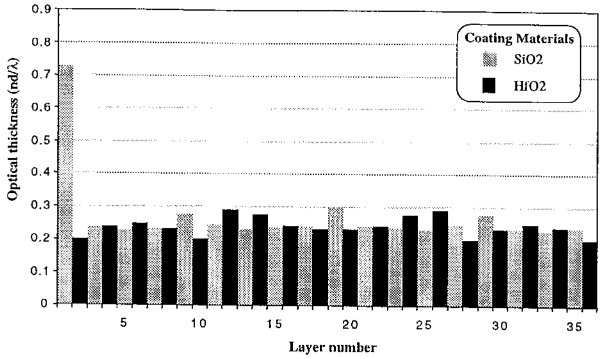
Fig. 1 Spectral plot of a Fabry-Perot bandpass filter at Brewster's angle with H = 1.97 and L = 1.45. Air $(1.1036H\ 1.2222L)^9\ (1.222L\ 1.1036H)^9$ Glass

Each of the designs were optimized using the Simplex method within the Essential Macleod Thin-Film Software[16] and analyzed for electric field profile, spectral bandwidth, layer thickness sensitivity, total thickness, and extinction ratio. Due to improvements realized in coating manufacturing of non-quarter-wave designs, the only restrictions placed on layer thickness was central mirror symmetry, although similar results could be realized without this restriction. The optimization targets were over a wavelength range of 1053 +/- 15 nm for appropriate spectral bandwidth to compensate for systematic centering errors during manufacturing.

The electric field is calculated assuming a 1 W/m^2 beam measured at normal incidence to a detector. Electric fields are calculated for both forward (air:film:substrate) and backward (substrate:film:air) propagating directions. The polarization bandwidth of the coating is determined by the region where the "P" polarization transmittance is greater than 0.98 and the "S" polarization transmittance is less than 0.01. The extinction ratio is equal to the "P" polarized transmittance divided by the "S" polarized transmittance in the center of the polarizing bandwidth. The required extinction ratio for the NIF polarizer is only 98:1 which is achieved when meeting the spectral requirements so this parameter is not used in comparing designs. The layer thickness sensitivity is determined by the manufacturing yield for achieving the above demanding spectral characteristics at 1053 nm determined by Monte Carlo analysis assuming a 1% standard deviation of random thickness errors. The actual manufacturability of the coating is a result of the combined systematic and random thickness errors, therefore a combined greater spectral bandwidth and lower layer sensitivity is desired.

3. RESULTS

A typical LWP design and electric field profiles of the forward and backward propagating beams are illustrated in figure 2. The presence of two electric field minimums in the overlayer is because of insufficient overcoat thickness at the first minimum to prevent delamination during laser exposure. The electric field maximums centered in the exterior high index layers and minimums in the silica layers present two predominate problems. The high index materials damage at lower electric field peaks than low index materials. Also the laser-induced thermal stresses between layers are maximized. The high index material expands due to the combination of electric field peaks, high absorption, and high thermal expansion



coefficient whereas the low index material has little expansion due to the electric field minimums, low absorption, and low thermal expansion coefficient.[17] The peak electric field in the forward propagating direction is 21.7 V/m and 39.0 V/m in the backward propagating direction. The spectral bandwidth of 37 nm is wider than the other designs attempted in this study. This was also the thinnest design at 6.2 μm physical thickness.

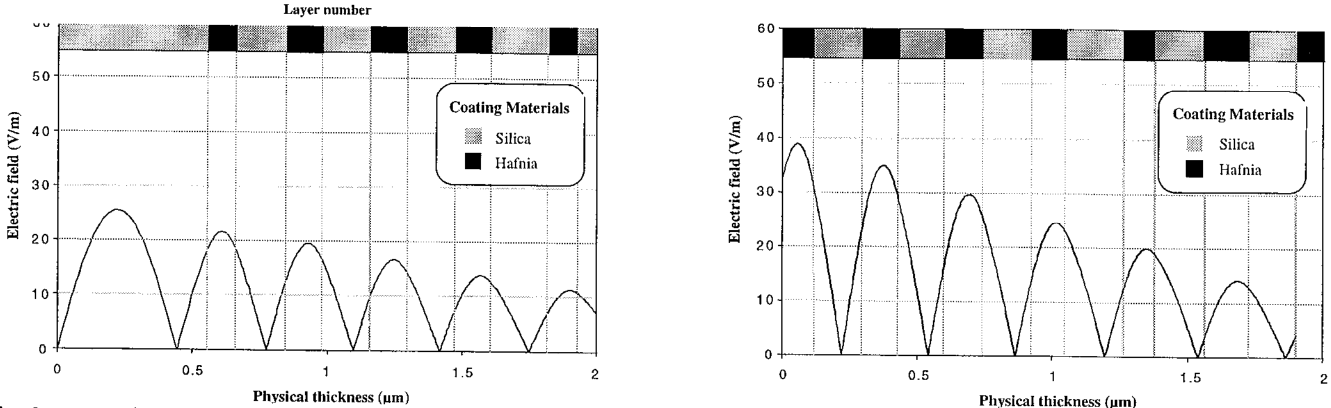
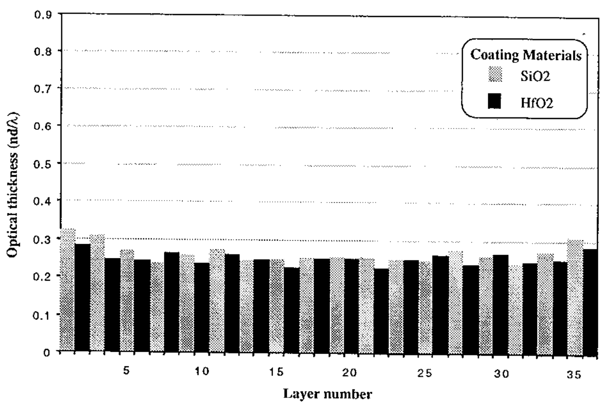


Fig. 2 Graphical representation of a SWP polarizer (top left). Electric field profile of the forward and backward propagating beam over the top and bottom 2 μm of the coating (bottom left and right respectively).



A typical SWP design has electric field minimums centered in the exterior high index layers as illustrated in figure 3. This address some of the problems associated with the LWP design, however, the electric fields are slightly higher at the multilayer interfaces at 22.1 V/m in the forward propagating direction and 39.5 V/m in the backward propagating direction. The spectral bandwidth of this design is reduced roughly 30% over the LWP design at 28 nm. The disadvantages of this design outweigh the benefits, however, a method is identified that could yield electric field reduction using different design structures.

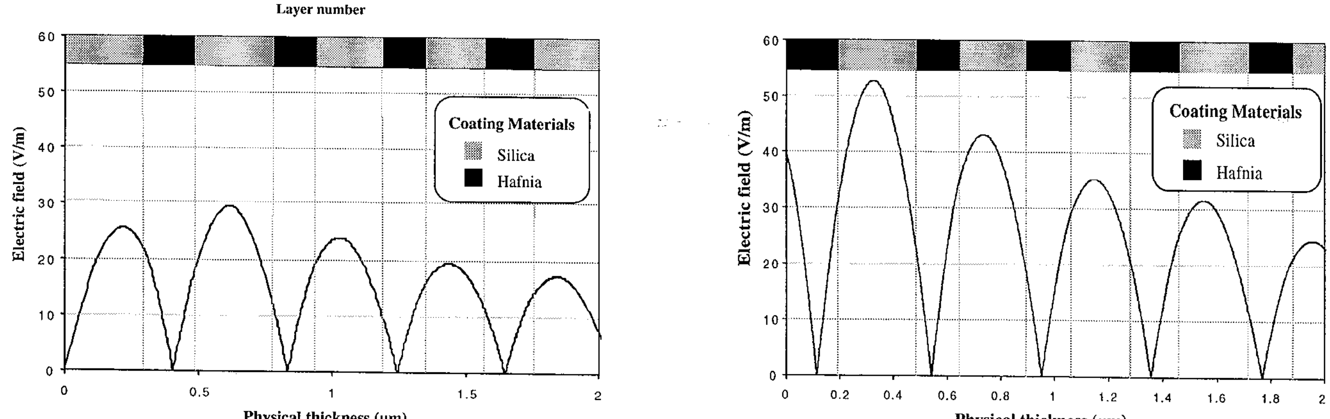
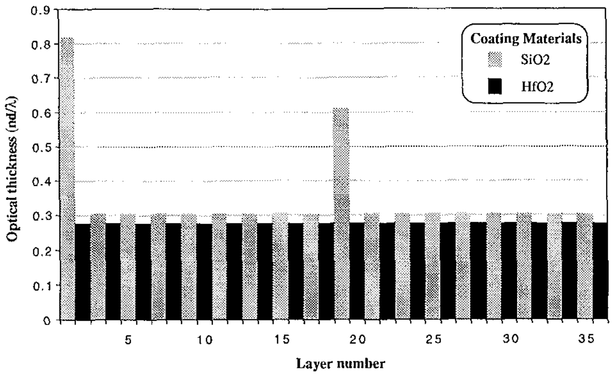


Fig. 3 Graphical representation of a SWP polarizer (top left). Electric field profile of the forward and backward propagating beam over the top and bottom 2 μm of the coating (bottom left and right respectively).



The properties of a Fabry-Perot bandpass design used on the long-wave edge of the bandpass are illustrated in figure 4. The electric field maximums are centered in the exterior high index layers similar to the LWP design. The highest electric fields are roughly 10% lower than the LWP design at the multilayer interfaces at 19.6 V/m in the forward propagating direction and 36.5 V/m in the backward propagating direction. The spectral bandwidth of this design is reduced roughly 40% at 23 nm, however, the central extinction ratio and manufacturing yield is highest of all the considered designs at 2000:1 and 95%, respectively.

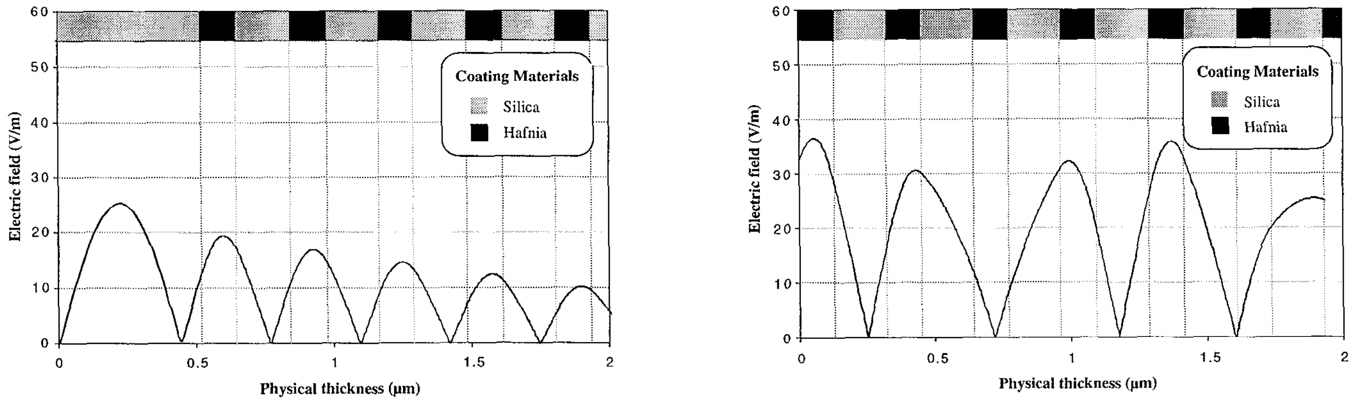
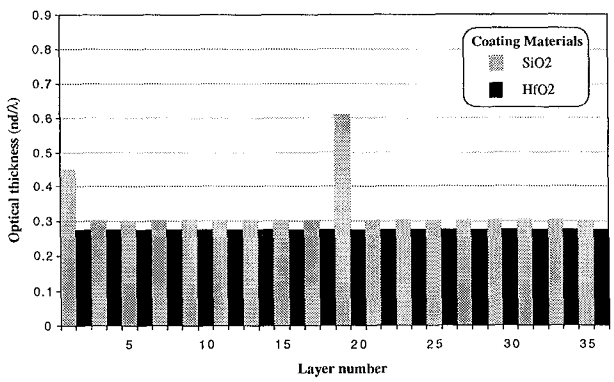


Fig. 4 Graphical representation of a long-wave centered bandpass polarizer (top left). Electric field profile of the forward and backward propagating beam over the top and bottom 2 μm of the coating (bottom left and right respectively).



When a Fabry-Perot bandpass design is used on the short-wave edge of the bandpass, the electric field minimums are centered in the exterior high index layers like the SWP design as illustrated in figure 5. The highest electric fields are roughly 20% lower than the LWP design at the multilayer interfaces at 16.9 V/m and 30.8 V/m in the forward and backward propagating direction respectively. The spectral bandwidth of only 18 nm is the least of the six of designs and roughly 50% of the LWP design. A manufacturing yield of 89% would be realized for a 1% standard deviation in random thickness errors, however systematic centering errors would be particularly troublesome for manufacturing this design.

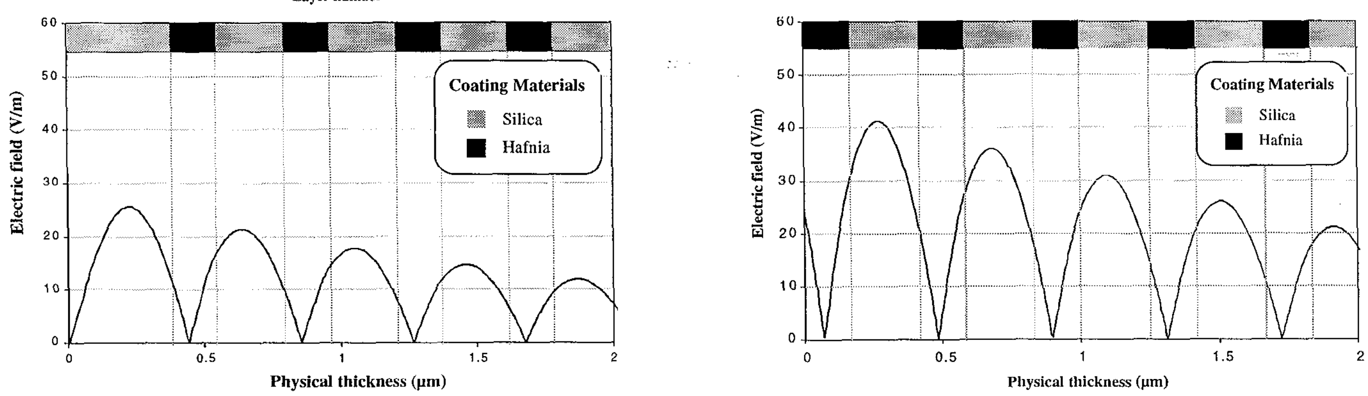
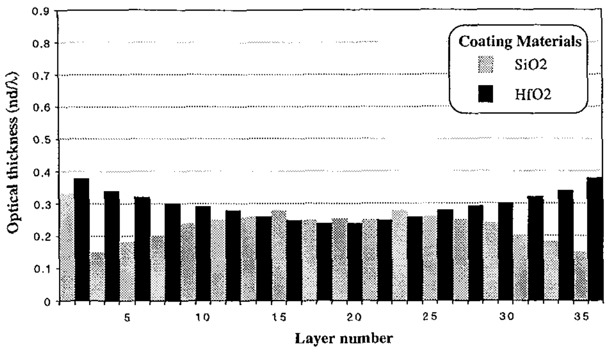
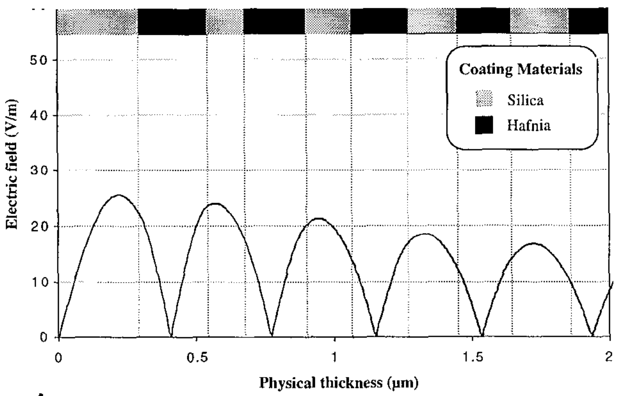


Fig. 5 Graphical representation of a short-wave centered bandpass polarizer (top left). Electric field profile of the forward and backward propagating beam over the top and bottom 2 μm of the coating (bottom left and right respectively).



Thick high index layers in a LWP design have been used to significantly reduce backward propagating electric fields while not affecting the forward propagating electric field.[9] When using this approach, but applying it to a SWP design to center the electric field minimums in the exterior high index layers, the results illustrated in figure 6 demonstrate roughly 10% higher electric fields for light propagating in either direction than the LWP design. In fact this design performs poorly on all of the evaluated criteria.



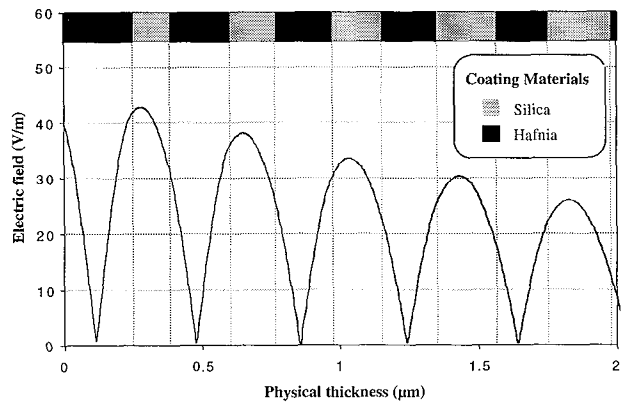
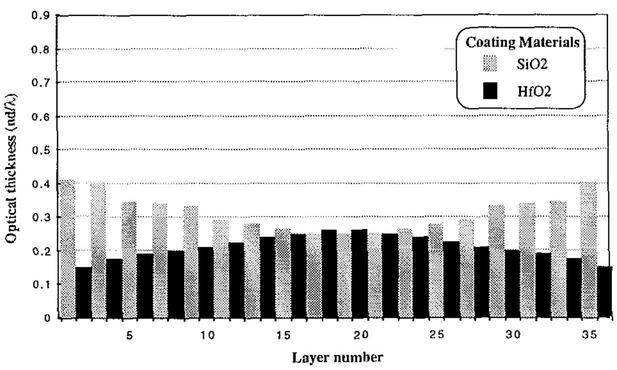
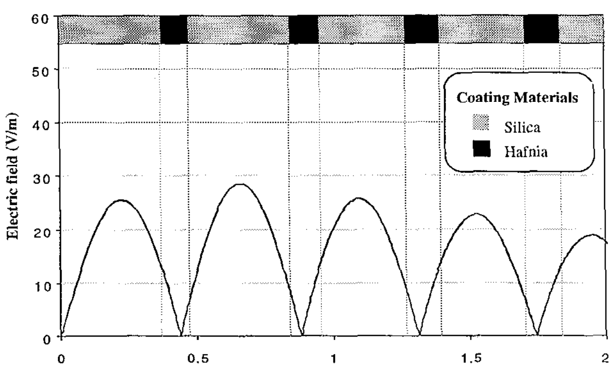


Fig. 6 Graphical representation of a SWP polarizer with thick hafnia layers (top left). Electric field profile of the forward and backward propagating beam over the top and bottom 2 μm of the coating (bottom left and right respectively).



Another approach previously published is the addition of pairs of thin high and thick low index layers to an unoptimized LWP polarizer design, thus utilizing the same design strategy as non-quarter-wave exterior layer pairs for electric field reduction in high reflectors.[5] This work addressed only forward propagating beams of unoptimized designs, however the electric field reduction was dramatic. This design strategy was applied to an optimized SWP design to realize electric field minimums in the exterior high index layers, but with a smoother profile of thick to thin layers with central symmetry, and restrictions on minimum layer thickness for improved manufacturability. As illustrated in figure 7, this design has the lowest electric



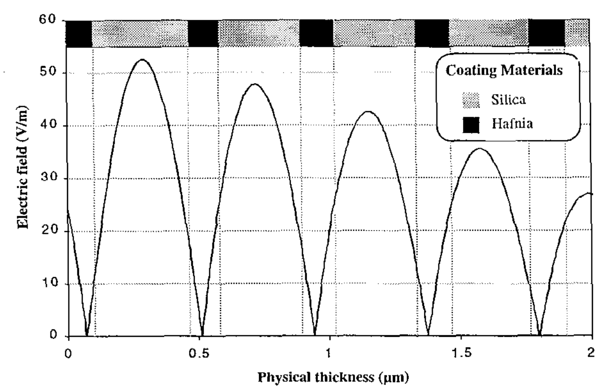


Fig. 7 Graphical representation of a SWP polarizer with thick hafnia layers (top left). Electric field profile of the forward and backward propagating beam over the top and bottom 2 μm of the coating (bottom left and right respectively).

fields of any of the designs attempted at 14.1 V/m and 25.8 V/m in the forward and backward propagating direction, respectively.

As is the case for most coating design, a trade off must be made between different performance criteria. When comparing the performance of the designs in table 1 with minimal electric field in the high index layers they also unfortunately have a reduced spectral bandwidth and manufacturing yield. However the SWP design with thin hafnia layers has a 35% electric field reduction so may warrant the 5-25% penalties in bandwidth, yield, and thickness.

Design	Normalized peak electric field in hafnia layers		Normalized polarization bandwidth	Normalized manufacturing yield	Normalized total thickness	Normalized central extinction ratio
	Forward (V/m)	Backward (V/m)				
Edge filter (LWP)	1.54	1.51	1.00	0.98	1.00	0.74
Edge filter (SWP)	1.57	1.53	0.76	0.96	1.21	0.65
Fabry-Perot bandpass	1.39	1.41	0.62	1.00	1.02	1.00
Fabry-Perot bandpass	1.20	1.19	0.49	0.94	1.27	0.86
Edge filter (SWP) (thick hafnia layers)	1.67	1.62	0.68	0.88	1.53	0.60
Edge filter (SWP) (thin hafnia layers)	1.00	1.00	0.81	0.95	1.24	0.47

Table 1. Summary of performance characteristics of polarizer designs

4. CONCLUSION

The electric field minimums in a polarizer coating can be transferred to the outer hafnia layers by optimizing a SWP edge filter design. For proper design construction, this can lead to a decrease in the electric field at the layer interfaces, which can limit the damage threshold of a polarizer multilayer coating. The electric field minimums in the high index layers and peaks in low index layers can also reduce thermal-induced stress gradients between layers. However the cost of this improvement is the reduction of spectral bandwidth, extinction ratio, and manufacturing yield. This design also has an increase in the manufacturing time due to greater overall design thickness. These reductions in performance may be tolerable if an adequate damage threshold improvement is realized.

5. AKNOWLEDGEMENTS

The author would like to acknowledge the support of Kerri Widergren in preparing this manuscript. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

6. REFERENCES

1) Bookless, W. A., Wheatcraft, D., "Energy & Technology Review: The National Ignition Facility," UCRL-52000-94-12 (Available from: National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161) **17** (1994).
2) Van Wonterghem, B. M., Murray, J. R., Campbell, J. H., Speck, D. R., Barker, C. E., Smith, I. C., Browning, D. F., Appl. Opt. **36**, 4932-4953 (1997).
3) Gill, D. H., Newnam, B. E., and McLeod, J., "Use of non-quarter-wave designs to increase the damage resistance of reflectors at 532 and 1064 nanometers," in *Laser-Induced Damage in Optical Materials: 1977*, A. J. Glass and A. H. Guenther, eds., NBS Spec. Publ. **509**, 260-270 (1978).
4) Apfel, J. H., "Optical coating design with reduced electric field intensity," Appl. Opt. **16**, 1880-1885 (1977).
5) Monga, J. C., "Multilayer thin-film polarizers with reduced electric-field intensity," J. of Modern Optics **36**, 769-784 (1989).

6) Weakley, S. C., Stolz, C. J., Wu, Z. L., Bevis, R. P., von Gunten, M. K., "Role of starting material composition in interfacial damage morphology of hafnia silica multilayer coatings," in *Laser-Induced Damage in Optical Materials: 1998*, G. J. Exarhos, A. H. Guenther, M. R. Kozlowski, K. L. Lewis, and M. J. Soileau, eds., Proc. SPIE **3578**, 137-143 (1999).
7) Dijon, J., Ravel, G., and André, B., "Thermomechanical model of mirror laser damage at 1.06 μm. Part 2: Flat bottom pits formation," in *Laser-Induced Damage in Optical Materials: 1998*, G. J. Exarhos, A. H. Guenther, M. R. Kozlowski, K. L. Lewis, and M. J. Soileau, eds., Proc. SPIE **3578**, 398-407 (1999).
8) Stolz, C. J., Génin, F. Y., Reitter, T. A., Molau, N., Bevis, R. P., von Gunten, M. K., Smith, D. J., Anzellotti, J. F., "Effect of SiO_2 overcoat thickness on laser damage morphology of HfO_2/ SiO_2 Brewster's angle polarizers at 1064 nm," in *Laser-Induced Damage in Optical Materials: 1996*, H. E. Bennett, A. H. Guenther, M. R. Kozlowski, B. E. Newnam, and M. J. Soileau, eds., Proc. SPIE **2966**, 265-272 (1997).
9) Motokoshi, S., Yoshida, H., Yoshida, K., Nakai, S., "Development of newly designed polarizer for high-power laser," Jpn. J. Appl. Phys. **32**, L1660-L1662 (1993).
10) Gu, P. F., and Tang, J. F., "Laser-induced damage resistance of thin-film polarizers prepared by ion-assisted deposition," Opt. Letters **19**, 81-83, (1994).
11) Buchman, W. W., "Index matching reduces peak electric fields in thin-film polarizers," Appl. Opt. **14**, 1220-1224 (1975).
12) Buchman, W. W., Holmes, S. J., and Woodberry, F. J., "Single-wavelength thin-film polarizers," J. Opt. Soc. Am. **61**, 1604-1606, (1971).
13) Songer, L. "The design and fabrication of a thin film polarizer," Optical Spectra, 49-50, (1978).
14) Blanc, D., Lissberger, P. H., Roy, A., "The design and optical measurement of thin film polarizers," Thin Solid Films, **57**, 191-198, (1979).
15) Schallenberg, U. B., Kaiser, N., "Damage-resistant thin-film plate polarizer," in Laser-Induced Damage In Optical Materials: 1996, H. E. Bennett, A. H. Guenther, M. R. Kozlowski, B. E. Newnam, and M. J. Soileau, eds. Proc. SPIE **2966**, 243-249 (1997).
16) Macleod, H. A., "Essential Macleod Optical Coating Design Program," Tuscon, AZ, 1997.
17) Génin, F. Y., Stolz, C. J., Reitter, T. A., and Kozlowski, M. R., "Effect of electric field distribution on the morphologies of laser-induced damage in hafnia-silica multilayer polarizers," in *Laser-Induced Damage in Optical Materials: 1996*, H. E. Bennett, A. H. Guenther, M. R. Kozlowski, B. E. Newnam, and M. J. Soileau, eds., Proc. SPIE **2966**, 342-353 (1997).